

MULTI DIMENSIONAL MODELLING OF A HIGH PRESSURE NATURAL  
GAS FUEL INJECTION PROCESS IN PRECHAMBER OF A SINGLE  
CYLINDER FOUR-STROKE ENGINE

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## ABSTRACT

This thesis deals with the numerical setup of a simulation for compressed natural gas in spark ignition engine with pre-chamber for the full cycle four-stroke engine using Computational Fluid Dynamics (CFD). Single-cylinder Yamaha FZ 150i engine is used as the base line engine design for the simulation. The engine is modified by replacing the pre-chamber at the spark plug hole. This study is focused on the combustion model with different ignition and injection timing. 2000 revolution per minute (rpm) and 500 iterations are set as the tested speed and number of iterations per time step respectively. This simulation is started from intake valve open until exhaust valve close as a completed cycle of engine. Turbulence is captured using k- $\epsilon$ -realizable model. This simulation is divided in 2 cases. Case 1 is set for study the effect of injection timing while Case 2 is set for study the effect of ignition timing. The injection pressure is set 20 bar and 15° crank angle (CA) of injection period. The injection timing that used are 40° before top dead centre (BTDC), 50° BTDC and 60° BTDC while the ignition timing that used are 20° BTDC, 30° BTDC, and 40° BTDC at the 50° CA BTDC. The predicted maximum pressure due to the injection and ignition timing is 27 bar while maximum temperature is 1200 K. For further simulation, more data from experimental work is needed especially pressure and temperature.

## ABSTRAK

Tesis ini berkaitan dengan kajian berangka tentang simulasi untuk gas asli termampat di dalam enjin pencucuhan api dengan pra-ruang sebagai bahagian tambahan untuk kitaran penuh enjin empat lejang menggunakan Dinamik Bendalir Komputeran (CFD). Enjin satu silinder Yamaha FZ 150i digunakan sebagai reka bentuk asas enjin bagi model simulasi. Enjin diubahsuai dengan menggantikan pra-ruang di lubang palam pencucuh. Kajian ini tertumpu kepada model pembakaran dengan pencucuhan yang berbeza dan masa suntikan. 2000 revolusi per minit (rpm) dan 500 iterasi ditetapkan sebagai kelajuan diuji dan bilangan itersai satu masa masing-masing. Simulasi ini bermula dari injap pengambilan dibuka sehingga penutupan injap ekzos sebagai kitaran lengkap enjin. Pergolakan ditangkap menggunakan model k- $\epsilon$ -realisasi. Simulasi ini dibahagikan dalam 2 kes. Kes 1 ditetapkan untuk mengkaji kesan masa suntikan manakala Kes 2 ditetapkan untuk kajian kesan masa penyalaan. Tekanan suntikan ditetapkan 20 bar dan 15 ° CA tempoh suntikan. Masa suntikan yang digunakan adalah 40 ° BTDC, 50 ° BTDC dan 60 ° BTDC manakala masa penyalaan yang digunakan ialah 20 ° BTDC, 30 ° BTDC, dan 40 ° BTDC pada 50 ° CA BTDC. Tekanan maksima yang dijangkakan akibat suntikan dan pemaasan penyalaan ialah 27 bar manakala suhu maksimum ialah 1200 K. Untuk simulasi lanjut, lebih banyak data daripada kerja eksperimental diperlukan terutama tekanan dan suhu.

## TABLE OF CONTENTS

	Page
<b>SUPERVISOR’S DECLARATION</b>	<b>ii</b>
<b>STUDENT’S DECLARATION</b>	<b>iii</b>
<b>DEDICATION</b>	<b>iv</b>
<b>ACKNOWLEDGEMENTS</b>	<b>v</b>
<b>ABSTRACT</b>	<b>vi</b>
<b>ABSTRAK</b>	<b>vii</b>
<b>TABLE OF CONTENTS</b>	<b>viii</b>
<b>LIST OF TABLES</b>	<b>xi</b>
<b>LIST OF FIGURES</b>	<b>xii</b>
<b>LIST OF SYMBOLS</b>	<b>xiii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xiv</b>
<b>CHAPTER 1      INTRODUCTION</b>	<b>1</b>
1.1                  Introduction	1
1.2                  Background Of Project	1
1.3                  Problem Statement	2
1.4                  Objectives	2
1.5                  Scope Of Study	2
1.6                  Flow Chart	3
1.7                  Summary	4
<b>CHAPTER 2      LITERATURE REVIEW</b>	<b>5</b>
2.1                  Introduction	5
2.2                  Internal Combustion Engine	5
2.2.1 Four-Stroke and Two-Stroke	5
2.2.2 Spark Ignition and Compression Ignition Engine	9
2.2.3 Fuel Injection and Carburetors	11
2.3                  Precombustion Chamber	12
2.3.1 Prechamber Design	13

	2.3.2 Advantages and Disadvantages Of Pre-combustion Chamber	14
	2.3.3 Sequence of Pre-combustion Chamber Process	14
2.4	Direct Injection Strategy	15
	2.4.1 Ignition Timing and Control	15
	2.4.2 Injection Timing and Control	16
2.5	CFD Simulation	16
	2.5.1 Turbulence Model	17
<b>CHAPTER 3</b>	<b>METHODOLOGIES</b>	<b>18</b>
3.1	Introduction	18
3.2	Flow Chart For Methodologies	18
3.3	Baseline Engine Specification	19
3.4	Transient Engine Modeling	19
	3.4.1 Mesh Generation	21
3.5	CFD Simulation Using Fluent	23
	3.5.1 Turbulence Model	23
	3.5.2 Combustion Model	24
3.6	Boundary Condition Setup	24
3.7	Numerical Setup	25
	3.7.1 Injection Timing Setup	25
	3.7.2 Ignition Timing Setup	25
	3.7.3 Combustion Setup	26
	3.7.4 Event Definition	27
3.8	Limitation of Study	28

<b>CHAPTER 4</b>	<b>RESULT AND DISCUSSION</b>	<b>29</b>
4.1	Introduction	29
4.2	Contour of Intake Jet Flow	29
4.3	Progressive Combustion Visualization	31
4.4	Case I : Variable Injection Timing	46
	4.4.1 Pressure In Cylinder	47
	4.4.2 Temperature In Cylinder	48
4.5	Case II : Variable Ignition Timing	49
	4.5.1 Pressure In Cylinder	49
	4.5.2 Temperature In Cylinder	50
4.6	Summary	50
<b>CHAPTER 5</b>	<b>CONCLUSION AND RECOMMENDATION</b>	<b>51</b>
5.1	Conclusion	51
5.2	Recommendation	52
<b>REFERENCES</b>		<b>53</b>

## LIST OF TABLES

<b>Table No.</b>	<b>Title</b>	<b>Page</b>
3.1	Engine specification Yamaha FZ150i	19
3.2	Operating condition of simulation	25
3.3	Injection condition	25
3.4	Ignition condition	26
3.5	Event of full crank angle in single cylinder	27
4.1	Contour of temperature in different injection timing	31
4.2	Contour of mass fraction methane in different injection timing	35
4.3	Contour of temperature in different ignition timing	39
4.4	Contour of mass fraction methane in different ignition timing	43

## LIST OF FIGURES

<b>Figure No.</b>	<b>Title</b>	<b>Page</b>
1.1	Project flow chart	3
2.1	Basic geometry of reciprocating internal combustion engine	6
2.2	The four-stroke operating cycle	7
2.3	The two-stroke operating cycle.	8
2.4	Otto cycle	9
2.5	Diesel cycle	10
2.6	Electronic and mechanical injector	11
2.7	Basic carburetor	12
2.8	Example of cutaway of pre-chamber design	13
3.1	Flow chart process for methodology.	18
3.2	2-D Engine modeling using SOLIDWORK	21
3.3	Meshed model geometry	22
3.4	Detailed of dynamic mesh	22
4.1	Contour of intake jet flow	30
4.2	Pressure of different injection timing	47
4.3	Temperature of different injection timing	48
4.4	Pressure of different ignition timing	49
4.5	Temperature of different ignition timing	50



**LIST OF SYMBOLS**

$\kappa\text{-}\varepsilon$	k-epsilon
$\lambda$	fuel air ratio
$\mu$	micro
$^{\circ}$	degree
%	percentage
$\rho$	density
rpm	revolution per minute
$C_R$	compression ratio
$V_s$	swept volume
$V_c$	clearance volume
s	second

## LIST OF ABBREVIATIONS

2D	Two dimensional
ATDC	After top dead center
BDC	Bottom dead center
BTDC	Before top dead center
CA	Crank angle
CAD	Computational Aided Design
CFD	Computational Fluid Dynamics
CI	Compression ignition
CNG	Compressed natural gas
DI	Direct injection
DISI	Direct injection-spark ignition
ICE	Internal combustion engine
K	Kelvin
N	Newton
PA	Pascal
SI	Spark ignition
SOHC	Single Over-Head Cam
TDC	Top dead center

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 INTRODUCTION**

This chapter discuss the information about this project include background of project, problem statement, objectives and scope of project.

#### **1.2 BACKGROUND OF PROJECT**

Compressed Natural gas (CNG) is one of the alternative fuel that find that can be used as the vehicle fuel replacing the gasoline (petrol) or diesel fuel. In this project the engine used is gasoline engine with single cylinder that convert to the CNG engine.

To improve the combustion and emission performance of CNG DISI engines, the pre-chamber is designed to help combustion in air fuel-mixing process. This design is a function to make engine efficiency increase with the high temperature and pressure in combustion chamber without knocking. Air-fuel mixing process in the cylinder is affected by many parameters such as the compression, combustion chamber and precombustion chamber geometry, injection pressure, nozzle-hole number and arrangement and swirl intensity. In this case, the model of prechamber is designed in order to improve the engine performance. The importance of this study is investigating the influences of combustion flow in the prechamber in case injection and ignition timing were controlled.

### **1.3 PROBLEM STATEMENT**

The inclusion of pre-chamber to improve combustion in a spark ignited gasoline engine to run on compressed natural gas need to be investigated. This is because the inclusion of pre chamber has reduced the effective compression ration of the engine. As results, the cylinder pressure and temperature have become lower than the original engine configuration. Two methods of investigation have been proposed. One is to vary the injection timing and the other is by ignition timing. The effect of both strategies is evaluated primarily based on cylinder combustion pressure and temperature.

### **1.4 OBJECTIVES**

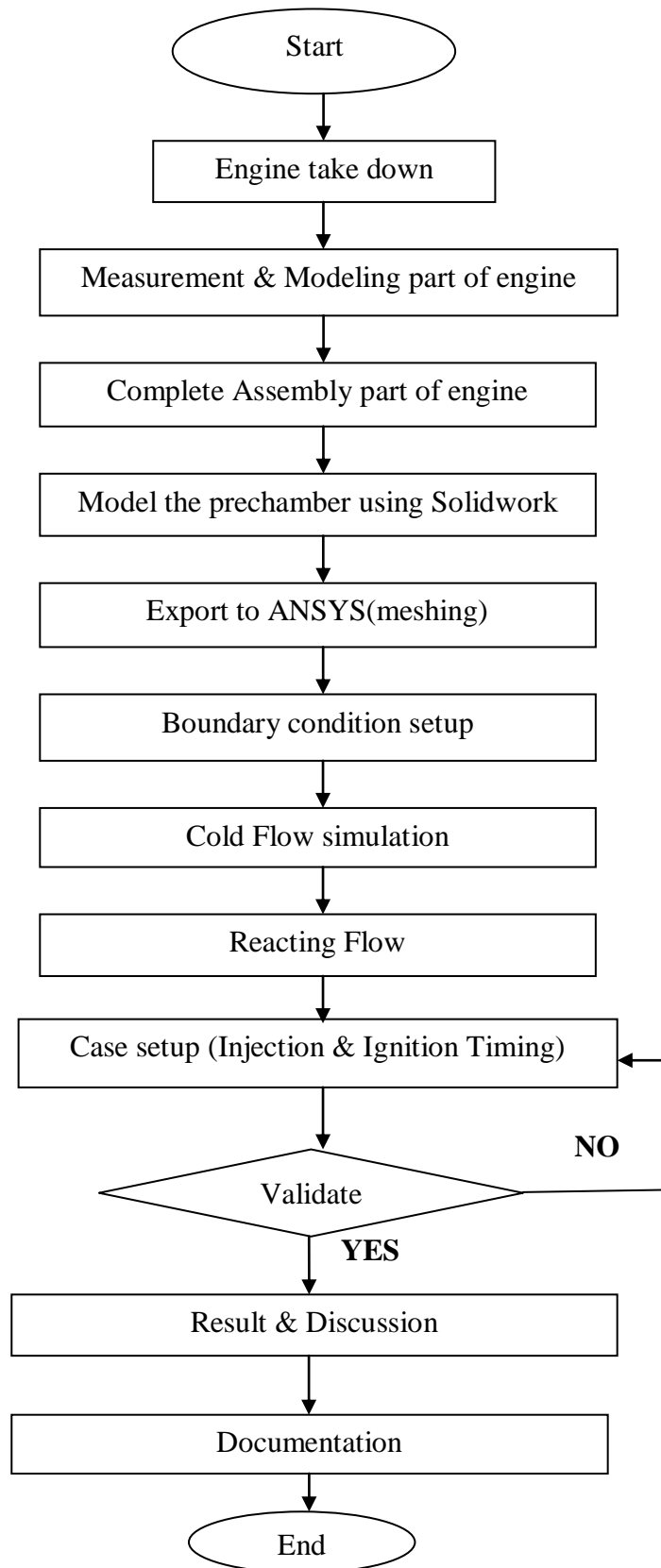
Based on the problem statement above, this project is conduct to simulate different injection and ignition timing for high pressure fuel injection in precombustion chamber of a single cylinder four-stroke ignition engine.

### **1.5 SCOPES OF STUDY**

The scope of this project are:

1. Structual design of main and prechamber in 2D geometry model based on Yamaha FZ150i engine dimension.
2. Design the precombustion chamber based on the actual main chamber volume where the prechamber volume less than 5% of the main volume.
3. Mesh generation and boundary condition setup
4. Simulation of cold flow and reacting flow process in precombustion chamber using CNG.

## 1.6 FLOW CHART



**Figure 1.1 :** Project flow chart

## **1.7 SUMMARY**

This chapter is generally described the project from the background, problem statement, objectives and scope of the project.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 INTRODUCTION**

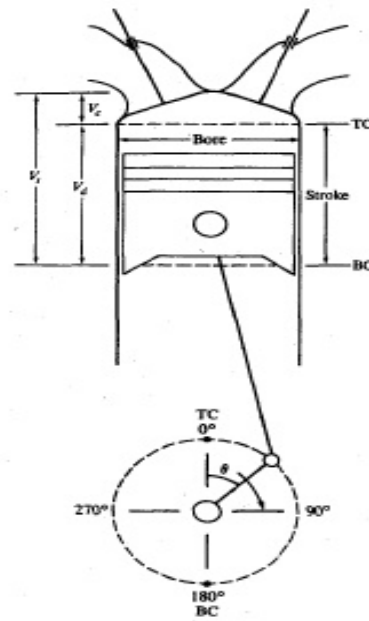
The purpose of this chapter is to provide a review of past research efforts related to spark ignition four-stroke engine, compressed natural gas as a fuel, internal combustion engine using prechamber model, direct injection control strategy and fluent analysis using ANSYS 12. The review is organized chronologically to offer insight to how past research efforts have laid the groundwork for subsequent studies, including the present research effort. The review is detailed so that the present research effort can be properly tailored to add to the present body of literature as well as to justify the scope and direction of the present research effort.

#### **2.2 INTERNAL COMBUSTION ENGINE**

An internal combustion engine means that engine uses the explosive combustion of fuel to move the piston and turns a crankshaft that then turns the car wheels via a chain or a drive shaft. The different types of fuel commonly used for car combustion engines are gasoline (or petrol), diesel, and kerosene.

##### **2.2.1 Four-Stroke and Two-Stroke Engine**

Four-stroke and two-stroke engine usually refer to the operating cycles of the engine. Most of the engine refers to reciprocating engines, where the piston moves back and forth in a cylinder and transmits power through a connecting rod and crank mechanism to the drive shaft (Heywood, 1988).



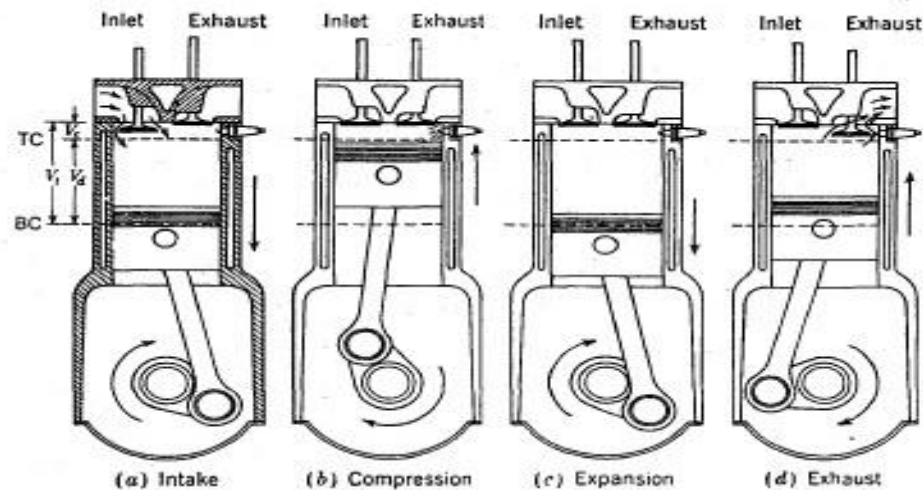
**Figure 2.1 :** Basic geometry of reciprocating internal combustion engine.

Source: Heywood 1988

The cyclical piston motion is produced by the rotation of the crank. The piston comes to rest at the top dead center (TDC) crank position and bottom dead center (BDC) crank position when the cylinder volume is a minimum or maximum. The minimum cylinder volume is called the clearance volume,  $V_c$ . Compression ratio,  $r_c$  is the ratio of maximum volume to the minimum volume. For spark ignition engine, typical value of  $r_c$  are 8 to 12 while for the compression ignition are 12 to 24.

The cycle reciprocating majority operate based on the four-stroke cycle (Heywood, 1988). In four-stroke engine, it has four cycles before complete the combustion. Each cylinder is required four strokes of its piston, and need two revolution of the crankshaft to complete the sequence of events which produces one power stroke. Both spark ignition (SI) and compression ignition (CI) using this cycle. This four cycle are intake stroke, compression stroke, expansion stroke and exhaust stroke.





**Figure 2.2:** The four-stroke operating cycle.

Source: Heywood 1988

The operating cycle to four-stroke start from intake stroke, which the piston at TDC and ends with the piston at BDC. In this stroke, fresh mixture is drawn into the cylinder. The inlet valve opens shortly before the stroke start to increase the mass inducted and closes after the stroke ends.

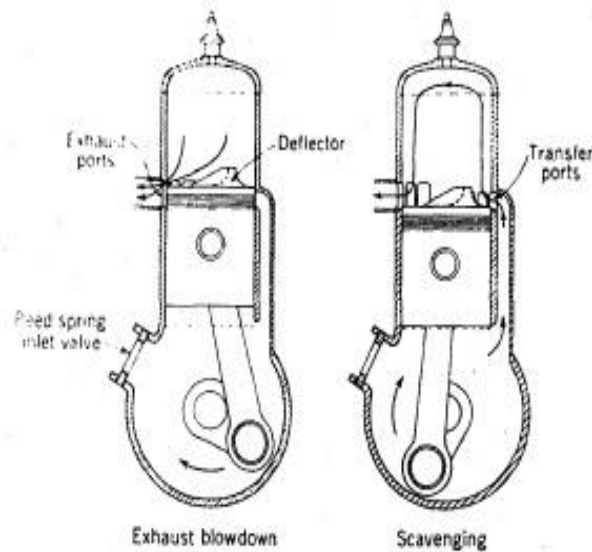
In the second stage of the cycle, a compression stroke is operated when the inlet and exhaust valves are closed and the mixture in the cylinder is compressed to a small fraction of its initial volume. At the end of this stroke, combustion initiated and the cylinder pressure rises more rapidly.

The piston starts at TDC and ends at BDC in expansion stroke. In this stroke, the high temperature, high pressure, and gases push the piston down and force the crank to rotate. During the expansion stroke, the piston had to do about five times as much work done of compression. As the piston approaches at BDC the exhaust valve is opened to initiate the exhaust process and drop the cylinder pressure to close to the exhaust pressure.

The last process in the four-stroke engine cycle is the exhaust stroke. During this stroke, gases remaining burned exit the cylinder because the cylinder pressure may be substantially higher than the exhaust pressure. Then they swept out by the

piston as it moves toward TDC. As the piston approaches TDC the inlet valve opens. After the exhaust valve closed, the cycle will be started again.

To obtain a higher power output from a given engine size, and a simpler valve design, the two-stroke cycle was developed (Heywood, 1988). The two-stroke cycle is applicable to both SI and CI engines.



**Figure 2.3:** The two-stroke operating cycle.

Source: Heywood 1988

For the design of two-stroke cycle in figure 2.3, it has ports in the cylinder liner. This ports operate opened and closed by piston motion, control the exhaust and inlet flows while the piston is close to BDC. In two-stroke cycle, it only have two process compare with four-stroke cycle that have four cycles to complete. This cycle are compression and expansion stroke.

A compression stroke which starts by closing the inlet and exhaust ports, and then compress the cylinder contents and draws a fresh charge into the crankcase. When the piston approaches TDC, combustion is initiated.

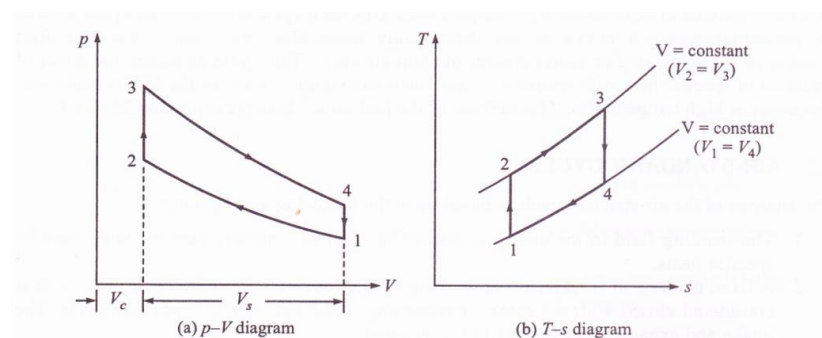
After the compression stroke, the piston moves down and approaches the BDC, so this called the expansion stroke when first the exhaust ports and the intake

ports are uncovered. Most of the burnt gases exit the cylinder in an exhaust blowdown process. When the inlet ports uncovered, the fresh charge which has been compressed in the crankcase flows into the cylinder. The piston and the ports are generally shaped to deflect the incoming charge from flowing directly into the exhaust ports.

### 2.2.2 Spark Ignition and Compression Ignition Engine

The internal combustion engine also can be classified by type of ignition on the engine (Pulkrabek, 2004). Two types of ignition that found in internal combustion engine are spark ignition (SI) and compression ignition (CI). An SI engine starts at the combustion process in each cycle by use of a spark plug. The spark plug gives a high voltage electrical discharge between two electrodes which ignites the air-fuel mixture in the combustion chamber surrounding the plug. In CI engine, the proses start when the air-fuel mixture self ignites due to high temperature in the combustion chamber caused by high compression.

Spark ignition usually found in the gasoline or petrol engine because they have higher self-ignition temperature. SI engine works on the Otto cycle (Gupta, 2006). A. Nicolaus Otto in 1876 proposed an ideal air-standard cycle with the constant volume heat addition, which formed the basis for the practical spark-ignition engines (petrol and gas engines). The cycle shown on  $p$ - $V$  and  $T$ - $s$  diagram in figure 2.4 (a) and figure 2.4 (b) respectively.

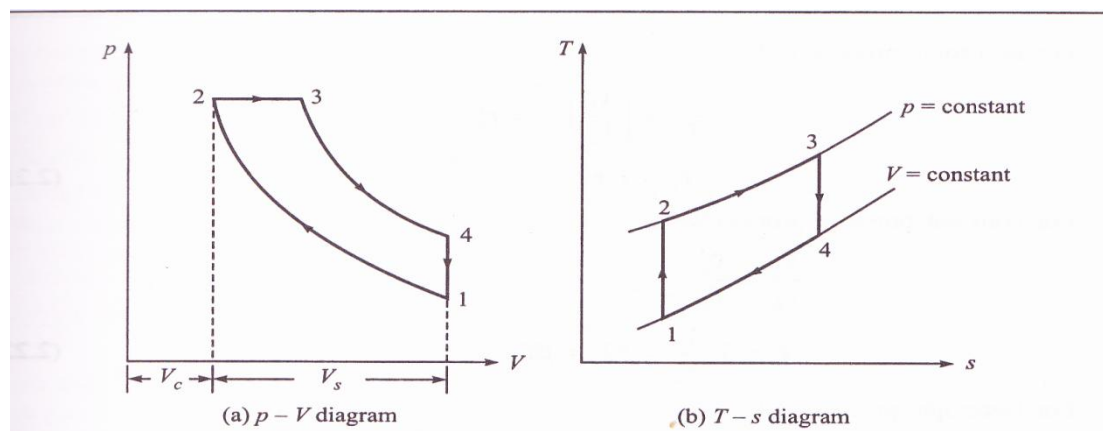


**Figure 2.4:** Otto cycle.

Source: Gupta 2006.

In SI engine, air and fuel mixture in gaseous form is inducted through the carburettor into the cylinder during the suction stroke. The throttle valve of the carburetor controls the quantity of charges. The quality of the charge remains almost fixed during normal running conditions at variable speed and load. The spark is required to burn the fuel. A compression ratio of this engine is 6 to 10.5. The upper limit is fixed by the anti-knock quality of fuel. The engine tends to knock at higher compression ratios.

Compression ignition engine also known as the diesel engine. A fuel having a lower self ignition temperature is desirable such as diesel oil. So, this engine will operate using the diesel cycle. Rudolf Diesel in 1892 introduced this diesel cycle (Gupta 2006). It is a theoretical cycle for slow speed compression ignition diesel engine. In this cycle, heat is added at constant pressure and rejected at constant volume. The  $p$ - $V$  diagram and  $T$ - $s$  diagram are shown in figure 2.5 (a) and figure 2.5 (b).



**Figure 2.5:** Diesel cycle.

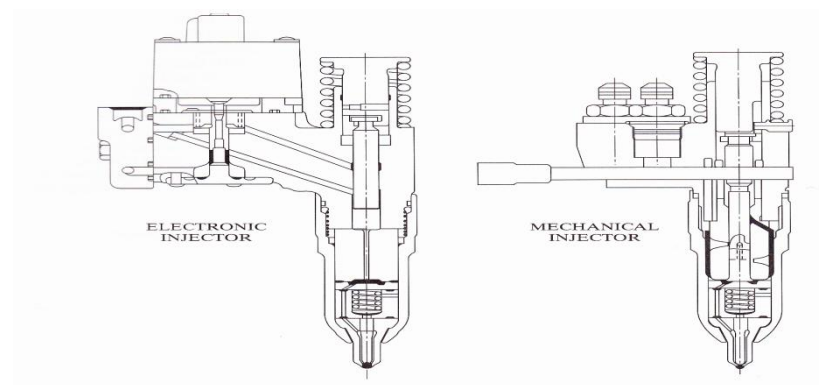
Source: Gupta 2006.

For CI engine, only air is introduced into the cylinder during the suction stroke and therefore the carburetor is not required. Fuel is injected at high pressure through the fuel injectors direct into the combustion chamber. The amount of air is fixed but the amount of fuel injected is varied by regulating the quantity of fuel in the

pump. The air-fuel ratio is varied at varying load. A compression ratio of CI engine is higher than gasoline engine. This compression ratio is 14 to 20.

### 2.2.3 Fuel Injection and Carburetors

Fuel injectors are nozzle that injected fuel into the intake air. They are normally controlled electronically, but mechanically controlled injectors, which are camoperated. The amount of fuel injected each cycle is controlled by injector pressure and time duration of injection.

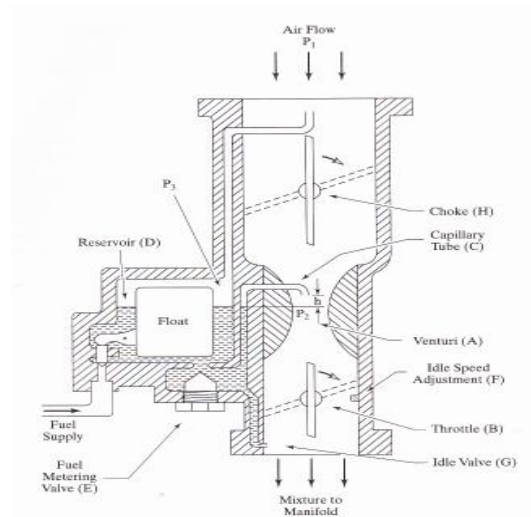


**Figure 2.6:** Electronic and mechanical injector.

Source: Pulkrabek 2004

An electric fuel injector consists of the following basic components; valve housing, magnetic plunger, solenoid coil, helical spring, fuel manifold, and pintle (needle valve). The fuel exits the injectors at velocities greater than 100m/sec, and flow rates of 3 to 4 gm/sec (Pulkrabek, 2004). In mechanically controlled injectors there is no solenoid coil, and the plunger is moved by the action of a camshaft.

Carburetors were used on most SI engine for several decades as means of adding fuel to the intake air. Carburetors are still found on few automobiles, but the vast majority of car engines use simpler, better controlled, more flexible fuel injection system.



**Figure 2.7:** Basic carburetor.

Source: Pulkrabek 2004.

Figure 2.7 shows that the basic carburetor is a venturi tube that mounted with a throttle plate and a capillary tube to the input fuel. It is usually mounted on the upstream end of the intake manifold, with all air entering the engine passing first through this venturi tube. Most of the time , there will be an air filter mounted directly on the upstream side of carburetor. Other main parts of the carburetor are the fuel reservoir, main metering needle valve, idle speed adjustment, idle valve, and the choke.

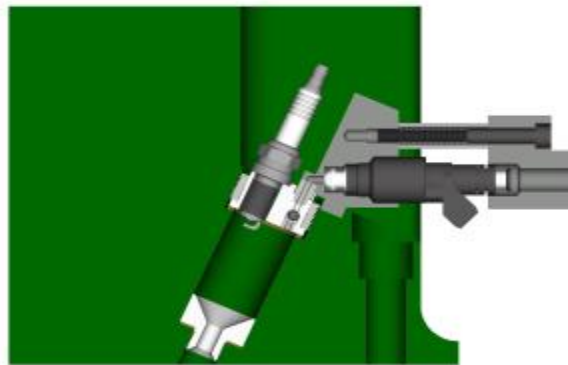
## 2.3 PRECOMBUSTION CHAMBER

Precombustion chamber or indirect injection have been used to generate vigorous charge motion during the compression stroke. There are categories of combustion chamber that can be classified as:

- 1) Swirl or turbelent chamber.
- 2) Precombustion chamber.
- 3) Air and energy cells.

### 2.3.1 Prechamber Design

Chambers are divided into two parts, which the main chamber is located between piston and cylinder head and the other one is prechamber that located at the cylinder head. Fuel is injected into prechamber and under full-load condition sufficient air to complete combustion not present in this chamber. These prechambers are usually small in size and are used as an ignition assist for very lean mixtures and to increase the combustion rate of large bore engines. The prechamber was located in the current spark plug hole location, with the spark plug cavity forming the prechamber chamber. The prechamber nozzle was mounted in the original spark plug hole.



**Figure 2.8:** Example of cutaway of prechamber design.

Source: John Kubesh 2002

The prechamber volume is equal to 20% of the total combustion chamber clearance volume, with one or more outlets leading to the main chamber. This volume large enough to contain sufficient fuel-air mixture to operate the engine at light loads over the speed range of engine. The prechamber volume also should be 20% or less for good results in terms of emissions and fuel economy (Gruden, 1976).

### **2.3.2 Advantages and Disadvantages of Precombustion Chamber**

There are many advantages of the prechamber combustion such as higher speed and brake mean effective pressure and the power with less smoke are feasible. Since the nozzle is at the side, there is no more room for the larger intake and exhaust valves, so volumetric efficiency will be higher. Using the prechamber, mechanical stress and noise become less because of the lower rate of pressure rise and the lower maximum pressure in the main chamber due to the throttling effect of throat. The engine will become smoother and quieter idling with precombustion chamber. And the most important that using precombustion chamber is less air pollution because the cleaner of exhaust.

Besides the advantage, this process also has disadvantages. The disadvantages of prechamber is higher specific fuel consumption that will resulting in poorer fuel economy. It is because of greater heat losses and pressure losses through the throat which result in lower thermal efficiency and higher pumping losses. The flow of combustion gases through the throat leads to thermal cracks in the cylinder head and creates sealing problems. When precombustion occurs, more thermal energy is lost to the exhaust gases. So, it may decrease the life of the exhaust valve which will run hotter and increase cracking and sealing problems of the exhaust manifold.

### **2.3.3 Sequence of Precombustion Chamber Process**

A precombustion chamber is connected to the main combustion chamber by spark plug hole. There are several steps occur during the combustion process.

During the compression stroke of the engine, air is forced into the precombustion chamber and the air become hot because its was compressed. At the beginning of injection , the precombustion chamber contains a definite volume of air.

As the injection begins, combustion starts in the precombustion chamber. The burning of the fuel, combined with the restricted passage to the main combustion